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METHOD FOR MANUFACTURING PIEZOELECTRIC ACTUATORS AND A PIEZOELECTRIC ACTUATOR

FIELD OF THE INVENTION

The present invention relates to a piezoelectric actuator which can be particularly used for actuating a fuel injector, as well as a method for manufacturing it.

BACKGROUND INFORMATION

Piezoelectric actuators, particularly for actuating fuel injectors, described in for example, German Patent Application No. 195 00 706 or German Patent No. 43 06 073. The piezoelectric actuators are composed of a plurality of piezoelectric layers stacked one over another which are each coated with an electrode on one surface. Usual piezoelectric actuators are composed of several hundred of piezoelectric layers stacked one over another in such a manner. In this manner, a relatively great length of actuating travel is achieved. As described in greater detail, for example, in German Patent 37 1 697, the electrodes of the individual piezoelectric layers must be alternately connected to a voltage source to generate an electrical field in individual layers which is oriented in the same direction. In the process, every other electrode is connected to a first pole of a voltage source, while the intermediate electrodes are connected to a second pole of a voltage source. Conventionally, as described in greater detail, for example, in British Patent No. 2 193 386, the electrodes, which extend up to the edge of the stacked piezoelectrical layers, are usually interconnected in the edge area on the outside. In a fully automated, large-scale manufacture, however, this contacting method requires considerable outlay, and is susceptible to faults, and, in addition, has the disadvantage that the electrodes, because they extend into the edge area, are not insulated against the surroundings so that the surface area of the piezoelectric actuators must be provided with an additional insulation.

SUBSTITUTE SPECIFICATION

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SUMMARY OF THE INVENTION

The method according to the present invention has the advantage that it can be used in a fully automated manufacture, and results in very low manufacturing expenses. The electrodes of the actuator are not contacted on the outside, but on the inside, using an electrically conductive paste which is introduced into connecting openings. Therefore, the contacting according to the present invention is almost impervious to faults and insusceptible to external mechanical damage. The piezoelectrical actuators are manufactured in parallel with each other in a highly integrated manufacturing process. A block including a plurality of piezoelectric actuators is split up into the individual actuators only at the end of the manufacture. In this manner, the manufacturing rate can be considerably increased. The same advantages ensue also for the actuator according to the present invention.

Advantageous embodiments and improvements of the manufacturing process specified in Claim 1 and the piezoelectric actuator specified in Claim 10, respectively, are made possible by the measures characterized in the subclaims.

If an edge area of the actuators is left free of the electrodes, the advantage ensues that the electrodes are reliably insulated from the surroundings of the actuator. Therefore, no further measures for insulating the electrodes are required. Since, in addition, the electrodes are contacted via connecting openings inside the actuator, all live components are completely insulated toward the outside. The susceptibility to failure of the actuator is markedly reduced.

In the intermediate areas between the individual actuators, perforation holes can be formed in the foils which form the piezoelectric layers. On one hand, these perforation holes are used as degassing ducts during the subsequent firing of the stacked foils. On the other hand, the perforation holes make it easier to separate the stacked arrangement into the individual actuators. In this context, the separation can be carried out by applying an electrical field to the electrodes of adjacent actuators in an opposite direction to the polarity. While one adjacent actuator contracts, the

other adjacent actuator expands. The resulting mechanical stress causes the actuators to break apart along the separating line predefined by the perforation holes. However, the perforation holes make it also easier to separate the actuators by sawing along the perforation line predefined by the perforation holes. Another suited separating method is water-jet cutting.

The metallic electrodes can be advantageously applied using a screen-printing technique, vapor depositing, or sputtering, it being advantageous not to apply the electrodes all-over, but in a, for example, netlike pattern for reasons of material saving and better adhesion promotion to the ceramic layer lying above.

BRIEF DESCRIPTION OF THE DRAWINGS

Fig. 1 shows a schematic representation of three foils made of piezoelectric ceramic material to be stacked one over another which are coated with electrodes, and provided with connecting openings and perforation holes, and

Fig. 2 shows a cut-off, perspective representation of a finished actuator.

DETAILED DESCRIPTION

Fig. 1 shows a perspective, schematic representation to illustrate the manufacturing process according to the present invention. Shown are three foils 1, 2, and 3 made of a still unfired piezoelectric ceramic material, i.e., of "green ceramic". A suitable material is, for example, lead-barium titanate ($PbBaTiO_2$). The ceramic material can be processed into thin foils, for example, by rolling, casting, or cutting, prior to the firing. The magnitude of the foil thickness lies at, for example, 0.1 mm, without the feasibility of the present invention being limited to this foil thickness. In a next processing step, the foils are coated with an electrically conductive material, preferably with a thin metal layer, on their upper side 4_1, 4_2, 4_3. For that, all known chemical and physical surface-coating methods, for example, vapor depositing, sputtering, or a screen-printing technique, are suitable. Electrodes 5_1 through 10_1, 5_2

through 10_2, and 5_3 through 10_3, can be applied all-over. In a screen-printing technique, however, a netlike pattern of the electrodes is expedient. In the embodiment shown in Fig. 1, in each case, one electrode 5_1, through 10_1, 5_2, through 10_2, and 5_3, through 10_3, of each foil 1, 2, and 3 is assigned to an actuator, respectively. Therefore, a plurality of actuators arranged in a laterally offset manner relative to each other are processed concurrently by the method according to the present invention, allowing the manufacturing expenses to be markedly reduced. In principle, it is also possible to assign not just one, but a plurality of electrodes to each actuator if this is desirable for individual application cases.

In an operation prior or subsequent to the coating, first connecting openings 11_1 through 16_1 in first foil 1, 11_2 through 16_2 in second foil 2, and 11_3 through 16_3 in third foil 3, as well as second connecting openings 17_1 through 22_1 in first foil 1, 17_2 through 22_2 in second foil 2, and 17_3 through 23_3 in third foil 3, are formed, for example, by punching or drilling in each foil layer 1, 2, and 3, respectively. Connecting openings 11 through 22 are used for contacting individual electrodes 5 through 10, which will still be discussed in greater detail. To achieve an alternating connection between the electrodes, second connecting openings 17_1 through 22_1 in first foil 1 are each surrounded by a cut-out 23_1 through 28_1, respectively, i.e., the electrode coating does not reach up to edge of second connecting openings 17_1 through 22_1, but the edge of electrodes 5_1 through 10_1 is spaced from the edge of second connecting openings 17_1 through 22_1. In similar manner, electrodes 5_3 through 10_3 of third foil 3 are provided with cut-outs 23_3 through 28_3 which surround second connecting openings 17_3 through 22_3. In the intermediate second foil layer, however, cut-outs 23_2 through 28_2 of electrodes 5_2 through 10_2 surround first connecting openings 11_2 through 16_2. The same is true for a further foil which is arranged above and adjoins first foil 1, and which is not shown, and a further foil which is arranged below and adjoins third foil 3, and which is not shown. This is why cut-outs 23 through 28, from foil layer to foil layer, are alternately assigned to first connecting openings 11 through 16 or second connecting openings 17 through 22, respectively.

Furthermore, in the embodiment shown in Fig. 1, each foil layer 1, 2, and 3 is provided with perforation holes 30_1, 30_2, and 30_3, respectively, which can be formed, for example, by punching or drilling concurrently with connecting openings 11 through 16 and second connecting openings 17 through 22. In this embodiment, perforation holes 30 are formed in a netlike manner, in each case marking the boundary line between the individual actuators manufactured concurrently using the method according to the present invention.

In each foil, netlike intermediate areas 31_1, and 31_2, and 31_3 are provided between electrodes 5_1 through 10_1, and 5_2 through 10_2, and 5_3 through 10_3, respectively, so that electrodes 5 through 10 do not reach up to the outer edge of the actuators, but are spaced from the edge marked by perforation holes 30. Perforation holes 30 are preferably arranged in intermediate areas 31 in lines running along the edges of the individual actuators. In this embodiment, actuators are manufactured which have a rectangular cross-section. To manufacture actuators having different cross-sections, the perforation holes are to be arranged in a varied manner correspondingly.

In a subsequent processing step, a plurality of foils, of which Fig. 1 only shows foils 1 through 3 in cutaway portions, are stacked one over another. To attain a sufficient length of actuator travel, preferably several hundred of the foils shown in Fig. 1 and treated as specified are stacked one over another. In the process, the individual foil layers are aligned relative to each other in such a way that both perforation holes 30, and first connecting openings 11 through 16, and second connecting openings 17 through 22 are positioned exactly one over another. This can be carried out, for example, in a fully automatic fashion using a reference-mark system capable of being mechanically or optically scanned. In Fig. 1, the stacking, that is, disposing in layers of the individual foils 1 through 3 is illustrated by arrows 40 through 43. As described above, the layer sequence of foils 1 through 3 is selected in such a manner that connecting openings 11 through 16, and 17 through 22, which are arranged one over another, respectively, are alternately surrounded by a cut-out 23 through 28 of electrodes 5 through 10 only in every other foil layer 1 through 3 so that electrodes 5 through 10 are alternately connected to first connecting openings

11 through 16 or second connecting openings 17 through 22.

In a further processing step, first connecting openings 11 through 16 and second connecting openings 17 through 22 are filled with a suitable, electrically conductive paste, for example, a metallization paste. The filling of connecting openings 11 through 16, and 17 through 22, respectively, can be carried out by drawing in with the assistance of negative pressure, or by pressing in. The electrically conductive paste is preferably introduced when the foils are already in the stacked condition. However, it is also conceivable to fill each individual foil with the electrically conductive paste prior to the stacking. Connecting openings 11 through 16, and 17 through 22 can also be designated as "via holes" so that the designation "via-fill process" is attached to the contacting method.

In a subsequent processing step, the stacked arrangement resulting from stacking foils 1 through 3 is dried under a suitable pressure at increased temperature, and, subsequently, fired at a suitable temperature. The firing temperature is preferably higher than 1,000° C, and is preferably in the range between 1,000° C and 1,500° C.

Subsequently, the fired stacked arrangement is split up into the individual actuators. In the case of a foil size of, for example, 15 x 20 cm, up to 200 individual actuators can be obtained from the stacked arrangement. The separation into the individual actuators is carried out, for example, by sawing or water-jet cutting. In this context, perforation holes 30 make the separation process easier, and mark the separation point.

According to another embodiment of the present invention, the separation of the stacked arrangement into the individual actuators is carried out by applying a voltage of different polarity to adjacent actuators. Due to the electrical field which forms in the individual layers of the actuator, and which is oriented in different direction among adjacent actuators, the adjacent actuators either contract or expand, depending on the field direction. Therefore, mechanical stress arises between the adjacent actuators, which, given suitable dimensioning of the electrical field strength

and the distance between the individual perforation holes 30, results in the separation of the actuators along the separation line predefined by perforation holes 30. This procedure is particularly cost-effective since no special separating device is needed.

A cut-off representation of an individual actuator is shown in Fig. 2. Discernible are layers 50_1 through 50_{15} made of piezoelectric ceramic material which are arranged one over another in a stack. Also discernible are electrodes 5_1 through 5_{15} of individual layers 50_1 through 50_{15}. As elucidated in Fig. 2 again, cut-outs 23_1 through 23_{15} of electrodes 5_1 through 5_{15} are alternately arranged in such a way that they alternately surround first connecting opening 11 and second connecting opening 17. By electrically conductive paste 53 which is filled in connecting openings 11 and 17, electrodes 5_1, 5_3, ... 5_{15} of every other layer are each connected to a first connecting wire 51 which is connected to the actuator, for example, by soldering, bonding, welding or the like. Intermediate electrodes 5_2, 5_4, ... 5_{14} are connected to a second connecting wire 52 via electrically conductive paste 53 which is introduced in second connecting openings 17. Therefore, the electrical field which, in response to the application of a voltage, forms in the actuator between connecting wires 51 and 52 is oriented in the same direction in all piezoelectric layers 50_1 through 50_{15} so that the contraction or expansion of each individual piezoelectric layer 15_1 through 15_{15} structurally adds up to a total length of travel of the piezoelectric actuator.

Also shown in Fig. 2 are broken-off perforation holes 30 in the edge area of the actuator. Because electrodes 5_1 through 5_{15} do not extend up to the edge area of the actuator, but are spaced from the edge by a distance a, a hermetical insulation of electrodes 5_2 through 5_{15} ensues. An additional insulation measure is to be provided just for topmost electrode 5_1. Preferably, the actuator is covered at its upper side by a suitable, electrically insulating encapsulating material. This encapsulating material can be applied in a planar manner even before the stacked arrangement is separated into the individual actuators. Furthermore, it is conceivable to apply an electrically insulating covering film on the upper side as a sealing layer.

Perforation holes 30 not only make it easier to separate the stacked arrangement into individual actuators, but, as degassing ducts, particularly assist the escape of gas during the drying and firing of the stacked arrangement. Using the method according to the present invention, it is possible to manufacture piezoelectric actuators which make do with an operating voltage of less than 150 V, and generate a force of more than 1,000 N combined with a length of actuating travel of 50 μm. By water-jet cutting, the stacked arrangement can be split up into individual actuators having nearly any cross-sectional area. Thus, for example, round, triangular or star-shaped actuators are manufacturable.